PREPRINT

REPORT OF THE IAU/IAG WORKING GROUP ON CARTOGRAPHIC COORDINATES AND ROTATIONAL ELEMENTS: 2003

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Abstract. Every three years the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements revises tables giving the directions of the north poles of rotation and the prime meridians of the planets, satellites, and asteroids. This report introduces a system of cartographic coordinates for asteroids and comets. A topographic reference surface for Mars is recommended. Tables for the rotational elements of the planets and satellites and size and shape of the planets and satellites are not included, since there were no changes to the values. They are available in the previous report (*Celestial Mechanics*, **82**, 83-110, 2002), a version of which is also available on a web site.

Key words: Cartographic coordinates, rotation axes, rotation periods, sizes, shapes, planets, satellites, asteroids, comets

1. Introduction

The IAU Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites was established as a consequence of resolutions adopted by Commissions 4 and 16 at the IAU General Assembly at Grenoble in 1976. The first report of the Working Group was presented to the General Assembly at Montreal in 1979 and published in the *Trans. IAU* **17B,** 72-79, 1980. The report with appendices was published in *Celestial Mechanics* **22,** 205-230, 1980. The guiding principles and conventions that were adopted by the Group and the rationale for their acceptance were presented in that report and its appendices. The second report of the Working Group was published in the *Trans. IAU* **18B,** 151-162, 1983, and also in *Celestial Mechanics* **29,** 309-321, 1983. The table summarizes the references to all the reports.

Report	General Assembly	*Celestial Mechanics and Dynamical Astronomy*
1	Montreal in 1979	**22,** 205-230, 1980.
2	Patras in 1982	**29,** 309-321, 1983.
3	New Delhi in 1985	**39,** 103-113, 1986.
4	Baltimore in 1988	**46,** 187-204, 1989.
5	Buenos Aires in 1991	**53,** 377-397, 1992
6	Hague in 1994	**63**, 127-148, 1996.
7	Kyoto in 1997	no report
8	Manchester in 2000	**82**, 83-110, 2002.

Preprints of the previous and this report can be found at the working group web site: http://astrogeology.usgs.gov/Projects/WGCCRE. The previous report is also available from the journal homepage. The tables are numbered in this report to be consistent with the numbering in the previous report.

This report introduces and recommends a consistent system of coordinates for both asteroids and comets. This system is not the same as the system for planets and satellites, which is not being changed. Pluto is included, as in the past, in the system of planets. It is recognized that the existence of two different systems has the potential for confusion, but the requirements for asteroids and comets seem sufficiently different that the use of two separate systems seems justified. This report includes the descriptions of the two systems for planets and satellites and asteroids and comets. The use of a uniform system for asteroids and comets is recommended. This will require some changes to previously published data. Note that in recognition of the introduction of this additional system, the name of the Working Group has been shortened to the Working Group on Cartographic Coordinates and Rotational Elements.

Since there are no changes to the rotational data for planets and satellites, size and shape parameters for the planets, and size and shape parameters of the satellites, those tables (Tables I, II, and V in the previous report, respectively) are not reprinted here. See one of the above web sites for the previous report with the tables. A topographic reference surface of Mars is recommended which is appropriate for use by missions to Mars. The accuracy of specification is only necessary for Mars missions. For some high accuracy purposes, it may be appropriate to introduce a relativistic proper time scale for Mars. The time scale, TCB, specified in the previous report was incorrect. The values given are appropriate for the time scales TT, TDB, or Teph to the accuracies given.

2. Definition of Rotational Elements for Planets and Satellites

Planetary coordinate systems are defined relative to their mean axis of rotation and various definitions of longitude depending on the body. The longitude systems of most of those bodies with observable rigid surfaces have been defined by references to a surface feature such as a crater. Approximate expressions for these rotational elements with respect to the International Celestial Reference Frame (ICRF) (Ma, et al, 1998) have been derived. The ICRF is the reference frame of the International Celestial Reference System and is itself epochless. There is a small (subarcsecond) rotation between the ICRF and the mean dynamical frame of J2000.0. The epoch J2000.0, which is January 1.5 (JD 2451545.0), TT, is the epoch for variable quantities, which are expressed in units of days (86400 SI seconds) or Julian centuries of 36525 days.

The north pole is that pole of rotation that lies on the north side of the invariable plane of the solar system. The direction of the north pole is specified by the value of its right ascension α_0 and declination δ_0, whereas the location of the prime meridian is specified by the angle that is measured along the planet's equator in an easterly direction with respect to the planet's north pole from the node Q (located at right ascension 90° + α_0) of the planet's equator on the standard equator to the point *B*, where the prime meridian crosses the planet's equator (see Figure 1). The right ascension of the point *Q* is 90° + α_0 and the inclination of the planet's equator to the standard equator is 90° - δ_0. Because the prime meridian is assumed to rotate uniformly with the planet, *W* accordingly varies linearly with time. In addition, α_0, δ_0, *and W* may vary with time due to a precession of the axis of rotation of the planet (or satellite). If *W* increases with time, the planet has a *direct* (or prograde) rotation, and if *W* decreases with time, the rotation is said to be *retrograde*.

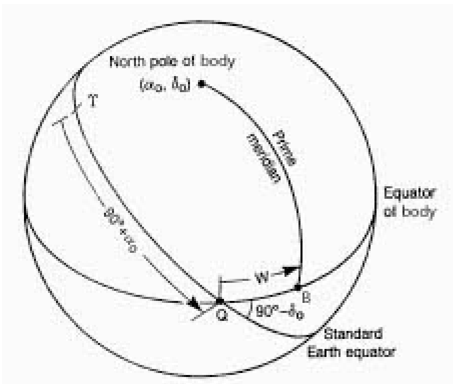

Figure 1. Reference system used to define orientation of the planets and their satellites.

In the absence of other information, the axis of rotation is assumed to be normal to the mean orbital plane; Mercury and most of the satellites are in this category. For many of the satellites, it is assumed that the rotation rate is equal to the mean orbital period.

The angle *W* specifies the ephemeris position of the prime meridian, and for planets or satellites without any accurately observable fixed surface features, the adopted expression for *W* defines the prime meridian and is not subject to correction. Where possible, however, the cartographic position of the prime meridian is defined by a suitable observable feature, and so the constants in the expression $W = W_0 + Wd$, where *d* is the interval in days from the standard epoch, are chosen so that the ephemeris position follows the motion of the cartographic position as closely as possible; in these cases the expression for *W* may require emendation in the future.

Recommended values of the constants in the expressions for α_0, δ_0, *and W*, in standard equatorial coordinates, are given for the planets and satellites in Tables I and II of the previous report. In general, these expressions should be accurate to one-tenth of a degree; however, two decimal places are given to assure consistency when changing coordinates systems. Zeros have sometimes been added to rate values (*W*) for computational consistency and are not an indication of significant accuracy. Additional decimal places are given in the expressions for Mercury, the Moon, Mars, Saturn, and Uranus, reflecting the greater confidence in their accuracy. Expressions for the Sun and Earth are given to a similar precision as those of the other bodies of the solar system and are for comparative purposes only. The recommended coordinate system for the Moon is the mean Earth/polar axis system (in contrast to the principal axis system).

The topographic reference surface of Mars is that specified in the final MOLA Mission Experiment Gridded Data Record (MEGDR) Products (Smith, et al. 2003). In particular, the 128 pixels/º resolution radius and topographic surfaces are recommended, although the lower resolution versions may be used where appropriate and documented, and for the areas poleward of +/-88º latitude.

3. Rotational Elements for Asteroids and Comets

For planets and satellites the IAU definition of north pole is the pole that lies above the invariant plane of the solar system, and the rotation can be either prograde or retrograde. For asteroids and comets, given substantial indirect evidence for large precession of the rotational poles of some comets, this first definition needs to be rethought, in anticipation of situations in which the pole that is clearly "north" in the IAU sense precesses over several decades to become clearly "south" in the IAU sense. Comet 2P/Encke, which is likely to be visited by spacecraft in the foreseeable future, is a prime example of a comet for which very large precession has been inferred.

There is also clear evidence for excited state rotation at least for comet 1P/Halley. In this case, the angular momentum vector moves around on the surface of the body. The rotational spin vector describes substantial excursions from the angular momentum vector during the course of the 7-day periodicity that is seen in the light curve. We can, therefore, anticipate cases in which the rotational spin pole moves back and forth between north and south on a time scale of days. So there is the issue of needing to change our definition of the rotational pole.

The choice of a rotational pole for a body in simple rotation with slow precession is straightforward. One can choose the pole that follows either the right-hand rule or the left-hand rule, and the right-hand rule is chosen here. This would be the "positive" pole to avoid confusion with the north-south terminology. Ideally one would like to choose a pole for excited state rotation that reduces to this definition as the rotational energy relaxes to the ground state. For SAM (short-axis mode) rotational states, it is possible to define a body-fixed axis that circulates in a generally complex pattern about the angular momentum vector and this approaches the simple right-hand rule definition as the rotational energy relaxes to the ground state of simple rotation. Presumably the appropriate body-fixed pole is the axis of maximum moment of inertia. However, the definition for a body in a LAM (long-axis mode) rotational state is not so obvious, since there is then complete rotation about the long axis of the body as well as rotation about a short axis. In this case, the pole should be taken as the minimum moment of inertia (the long axis of an ellipsoid) according to the right-hand rule.

Increasing longitude should also follow the right-hand rule rather than follow the rule that longitude should increase monotonically for an observer fixed in inertial space. With the above definitions of poles, the latter definition of longitude corresponds always to a left-hand rule for increasing longitude, since the concept of retrograde rotation is no longer relevant. The latter would correspond to the coordinates used for Eros by Thomas et al. (2002), (fortunately the positive pole of Eros is in the north) while the former corresponds to the sense of increasing longitude used by Miller et al. (2002).

For each asteroid and comet the positive pole of rotation is selected as the maximum or minimum moment of inertia according to whether there is short or long axis rotational state and according to the right-hand rule. So for asteroids and comets the positive pole is specified by the value of its right ascension α_0 and declination δ_0, whereas the location of the prime meridian is specified by the angle that is measured, along the body's equator in a right-hand system with respect to the body's positive pole, from the node Q (located at right ascension $90° + \alpha_0$) of the body's equator on the standard equator to the point B, where the prime meridian crosses the body's equator (see Figure 2). The right ascension of the point Q is $90° + \alpha_0$ and the inclination of the body's equator to the standard equator is $90° - \delta_0$. Because the prime meridian is assumed to rotate uniformly with the body, W accordingly varies linearly with time according to the right-hand rule. In addition, α_0, δ_0, *and* W may vary with time due to a precession of the axis of rotation of the body.

The angle W specifies the ephemeris position of the prime meridian, and for asteroids or comets without any accurately observable fixed surface features, the adopted expression for W defines the prime meridian and is not subject to correction. Where possible, however, the cartographic position of the prime meridian is defined by a suitable observable feature, and so the constants in the expression $W = W_0 + Wd$, where d is the interval in days from the standard epoch, are chosen so that the ephemeris position follows the motion of the cartographic position as closely as possible; in these cases the expression for W

may require emendation in the future. Table III gives the recommended rotation values for the direction of the positive pole of rotation and the prime meridian of selected asteroids and comets.

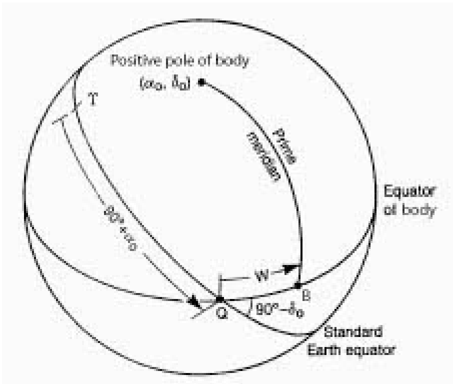

Figure 2. Reference system used to define orientation of the asteroids and comets.

Table III. Recommended rotation values for the direction of the positive pole of rotation and the prime meridian of selected asteroids and comets

d is the interval in days from the standard epoch, i.e. J2000.0 = 2000 January 1.5, i.e., JD 2451545.0 TT. α_0, δ_0, *and W* are as defined in the text.

243 Ida	α_0 =168°.76	
	δ_0 = -2°.88	
	W = 265°.95 - 1864°.6280070d	(a)
951 Gaspra	α_0 = 9°.47	
	δ_0 = 26°.70	
	W = 83°.67 + 1226°.9114850d	(b)
4 Vesta	α_0 = 301°	
	δ_0 = 41°	
	W = 292° + 1617°.332776d	
433 Eros	α_0 = 11°.35 ± 0.02	
	δ_0 = 17°.22 ± 0.02	
	W = 326°.07 + 1639°.38864745d	
6489 Golevka	α_0 = 228°	
	δ_0 = 33°	
	W = 000° + 59°.712d	(c)
19P/Borrelly	α_0 = 218°.5 ± 3	
	δ_0 = -12°.5 ± 3	
	W = 000° + 390°.0d	(c)

(a) The 0° meridian is defined by the crater Afon.
(b) The 0° meridian is defined by the crater Charax.
(c) Since only rotation rate information is available, the 0° meridian is currently arbitrarily defined with W_0 = 0°.

4. Definition of Cartographic Coordinate Systems for Planets and Satellites

In mathematical and geodetic terminology, the terms 'latitude' and 'longitude' refer to a right-hand spherical coordinate system in which latitude is defined as the angle between a vector passing through the origin of the spherical coordinate system and the equator, and longitude is the angle between the vector and the plane of the prime meridian measured in an eastern direction. This coordinate system, together with Cartesian coordinates, is used in most planetary computations, and is sometimes called the planetocentric coordinate system. The origin is the center of mass.

Because of astronomical tradition, planetographic coordinates (those commonly used on maps) may or may not be identical with traditional spherical coordinates. Planetographic coordinates are defined by guiding principles contained in a resolution passed at the fourteenth General Assembly of the IAU in 1970. These guiding principles state that:

(1) The rotational pole of a planet or satellite which lies on the north side of the invariable plane will be called north, and northern latitudes will be designated as positive.

(2) The planetographic longitude of the central meridian, as observed from a direction fixed with respect to an inertial system, will increase with time. The range of longitudes shall extend from 0° to 360°.

Thus, west longitudes (i.e., longitudes measured positively to the west) will be used when the rotation is prograde and east longitudes (i.e., longitudes measured positively to the east) when the rotation is retrograde. The origin is the center of mass. Also because of tradition, the Earth, Sun, and Moon do not conform with this definition. Their rotations are prograde and longitudes run both east and west 180°, or east 360°.

For planets and satellites, latitude is measured north and south of the equator; north latitudes are designated as positive. The planetographic latitude of a point on the reference surface is the angle between the equatorial plane and the normal to the reference surface at the point. In the planetographic system, the position of a point (P) not on the reference surface is specified by the planetographic latitude of the point (P') on the reference surface at which the normal passes through P and by the height (h) of P above P'.

The reference surfaces for some planets (such as Earth and Mars) are ellipsoids of revolution for which the radius at the equator (A) is larger than the polar semi-axis (C).

Calculations of the hydrostatic shapes of some of the satellites (Io, Mimas, Enceladus, and Miranda) indicate that their reference surfaces should be triaxial ellipsoids. Triaxial ellipsoids would render many computations more complicated, especially those related to map projections. Many projections would lose their elegant and popular properties. For this reason spherical reference surfaces are frequently used in mapping programs.

Many small bodies of the solar system (satellites, asteroids, and comet nuclei) have very irregular shapes. Sometimes spherical reference surfaces are used for computational convenience, but this approach does not preserve the area or shape characteristics of common map projections. Orthographic projections often are adopted for cartographic portrayal as these preserve the irregular appearance of the body without artificial distortion.

Table IV in the previous report gives size and shape parameters for the planets. These values are unchanged so are not repeated here. However, note that in that table average (AVG), north (N), and south (S) polar radii are given for Mars. For the purpose of adopting a best-fitting ellipsoid for Mars, the average polar radius should be used – the other values are for comparison only, e.g. to illustrate the large dichotomy in shape between the northern and southern hemispheres of Mars. In applications where these differences may cause problems, the earlier recommended topographic shape model for Mars should probably be used as a reference surface.

Table V in the previous report gives the size and shape of satellites where known. Only brightnesses are known for many of the newly discovered satellites. Poles and rotation rates are also not yet known for the new discoveries, so those satellites are not listed. Note that in the previous report in Table V, the RMS deviation from the ellipsoid for Helene (0.7 km) was listed under the Polar radius, which should have been blank.

5. Cartographic Coordinates for Asteroids and Comets

For large bodies, a spherical or ellipsoidal model shape has traditionally been defined for mapping, as in our past reports. For irregularly shaped bodies the ellipsoid is obviously useless, except perhaps for dynamical studies. For very irregular bodies, the concept of a reference ellipsoid ceases to be useful for most purposes. For these bodies, topographic shapes are usually represented by a grid of radii to the surface as a function of planetocentric latitude and longitude.

Another problem with small bodies is that two coordinates (i.e. spherical angular measures) may not uniquely identify a point on the surface of the body. In other words it is possible to have a line from the center of the object intersect the surface more than once. This can happen on large and even mostly ellipsoidal objects such as the Earth, because of such features as overhanging cliffs and natural bridges and arches. However on large bodies these features are relatively very small and often ignored at the scale of most topographic maps. For small bodies they may be fairly large relative to the size of the body. Example cases are on Eros (at a small patch west of Psyche), and certainly on Kleopatra (Ostro, 2000), possibly on Toutatis near its 'neck', and perhaps near the south pole of Ida, some radii may intersect the surface more than once. Even on small bodies this problem is usually restricted to small areas. But it still may make a planetocentric coordinate system difficult to use. Cartographers always have *ad hoc* tricks for a specific map, such as interpolating across the problem area from areas which are uniquely defined, or by showing overlapping contours. A Cartesian or other coordinate geometry may be preferable for arbitrarily complex shapes, such as a toroidal comet nucleus, where an active region ate its way through the nucleus. Such coordinate geometries may also be useful for irregular bodies imaged only on one side, such as for 19P/Borrelly and 81P/Wild 2.

With the introduction of large mass storage to computer systems, digital cartography has become increasingly popular. Cartographic databases are important when considering irregularly shaped bodies and other bodies, where the surface can be described by a file containing the coordinates for each pixel. In this case the reference sphere has shrunk to a unit sphere. Other parameters such as brightness, gravity, etc., if known, can be associated with each pixel. With proper programming, pictorial and projected views of the body can then be displayed.

Taking all of this into account, the recommendation here is that longitudes on asteroids and comets should be measured positively from 0 to 360 degrees in a right-hand system from a designated prime meridian. The origin is the center of mass, to the extent known.

Latitude is measured positive and negative from the equator; latitudes toward the positive pole are designated as positive. For regular shaped bodies the cartographic latitude of a point on the reference surface is the angle between the equatorial plane and the normal to the reference surface at the point. In the cartographic system, the position of a point (P) not on the reference surface is specified by the cartographic latitude of the point (P') on the reference surface at which the normal passes through P and by the height (h) of P above P'.

For irregular bodies orthographic digital projections often are adopted for cartographic portrayal as these preserve the irregular appearance of the body without artificial distortion. These projections should follow the right-hand rule.

A uniform system is recommended for asteroids and comets. This requires some changes in previous values given and in values specified for nomenclature. The problem of changing the nomenclature database (http://planetarynames.wr.usgs.gov/) is fairly straightforward. The problem comes down to: a) changing the sign of the latitude for the 25 named features on Ida, b) changing the longitudes from west to positive for the named features on Eros, Ida, Gaspra, Dactyl, and Mathilde, and c) adding explanatory text describing the "old" and "new" coordinate systems.

Table VI contains data on the size and shape of selected asteroids and comets. The first column gives the effective radius of the body and an estimate of the accuracy of this measurement. This effective radius is for a sphere of equivalent volume. The next three columns give estimates of the radii measured along the three principal axes.

The uncertainties in the values for the radii in Table VI are generally those of the authors, and, as such, frequently have different meanings. Sometimes they are standard errors of a particular data set, sometimes simply an estimate or expression of confidence.

The radii given in the tables are not necessarily the appropriate values to be used in dynamical studies; the radius actually used to derive a value for the dynamical form factor (J_2) (for example) should always be used in conjunction with it.

Table VI. Size and shape parameters of selected asteroids and comets

Asteroid	Effective Radius (km)	Radii measured along principal axes (km)	(km)	(km)
243 Ida	15.65 ± 0.6	26.8	12.0	7.6
951 Gaspra	6.1 ± 0.4	9.1	5.2	4.4
216 Kleopatra		108.5	47	40.5
433 Eros	8.45 ± 0.02			
6489 Golevka	0.265 ± 0.015			
3908 Nyx	0.500 ± 0.075			
1998JM8	3.5			
1998ML14	0.5			
19P/Borrelly	-	4.22+/-0.05	3.5+/-0.2	-

Appendix – Changes Since the Last Report

This appendix summarizes the changes that have been made to the tables since the 2000 report *(Celestial Mechanics and Dynamical Astronomy* **82,** 83-110, 2002).

A right-handed cartographic coordinate system has been introduced and recommended for asteroids and comets, which is different than the system used for planets and satellites.

A topographic reference surface for Mars has been recommended.

The pole and rotation of 6489 Golevka is from Hudson et al. (2000).

The positive pole position of 19P/Borrelly is based on the location of the jet α, is probably only valid for the time of the *Deep Space 1* encounter, and is given by Soderblom et al. (2002). The rotation rate is derived from the 26 hour period determined by Mueller and Samarasinha (2001).

In Table VI the concept of an effective radius has been introduced to replace the more ambiguous concept of mean radius.

The radii of 6489 Golevka, 3908 Nyx, 1998 JM8, and 1998 ML14 are from Hudson et al. (2000), Benner et al. (2002), Benner et al. (2002), and Ostro et al. (2001), respectively.

The radii of 19P/Borrelly are estimates from Kirk (personal communication, 2003). These are based on extrapolations of a digital terrain model of the visible portions of the comet (4.28 km x 3.00 km, with a minimum width of 1.38 km, all ± 0.05 km) to likely maximum radii, from work published by Kirk et al. (2004).

Acknowledgement

We appreciate the efforts of Mark Rosiek, who assisted in the creation of the Figures.

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